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13. ABSTRACT *(Maximum 200 words)*
The goal of this research program was to elucidate the hot electron physics of ACTFEL devices with particular emphasis on: 1) hot electron transport, 2) defect state hot electron sourcing and trapping, and 3) hot electron-induced ACTFEL aging. Highlights of our research accomplishments are summarized in terms of these three topical categories.

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HOT ELECTRON PHYSICS OF ALTERNATING-CURRENT THIN-FILM ELECTROLUMINESCENT DEVICES

Final Report

J.F. Wager and S.M. Goodnick

21 October 1994

U.S. Army Research Center

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Oregon State University

HOT ELECTRON PHYSICS OF ALTERNATING-CURRENT THIN-FILM ELECTROLUMINESCENT DEVICES

I. Statement of the Problem Studied

The goal of this research program was to elucidate the hot electron physics of ACTFEL devices with particular emphasis on: 1) hot electron transport, 2) defect state hot electron sourcing and trapping, and 3) hot electron-induced ACTFEL aging. Highlights of our research accomplishments are summarized in terms of these three topical categories.

II. Summary of Important Results

1. Hot Electron Transport

(a) Monte Carlo Simulation of High-Field Transport in ZnS

Ensemble Monte Carlo simulation of high-field transport in bulk ZnS are performed.[1] Scattering mechanisms associated with polar optical phonons, acoustic phonons (through deformation potential coupling), intervalley scattering, and impurities (neutral and ionized) are included in a nonparabolic, three-valley model. Simulation indicates that the polar optical phonon and intervalley scattering mechanisms are dominant, whereas neutral and ionized impurity scattering are of no importance in determining the high-field transport in bulk ZnS. The simulated results show that energetic electrons are available for impact excitation at fields exceeding 1 MV/cm and that transient effects are of negligible importance in explaining the measured efficiencies of ACTFEL devices.

A full band Monte Carlo simulation of the high-field electron transport in the ZnS phosphor layer of an ACTFEL device is presented.[2] The simulation includes an empirical pseudopotential bandstructure for ZnS and all the pertinent electron scattering mechanisms. Band-to-band impact ionization and impact excitation of luminescence centers (such as Mn^{2+}), two threshold phenomena which are crucial to the operation of ACTFEL devices, are included in the ensemble Monte Carlo calculations. The steady-state energy distributions of electrons in the ZnS layer are computed for typical phosphor fields (1-2 MV/cm). The results reveal a substantial fraction of electrons with energies in excess of the excitation threshold energies of typical luminescent centers such as manganese and terbium. Computed quantum yields of the carriers transiting the phosphor layer exhibit an approximately linear increase with increasing phosphor field. At high fields, when impact ionization begins to significantly affect the transport, the excitation-limited quantum yield, and hence the brightness of an ACTFEL device, tends to exhibit saturation.

(b) Hot Electron Luminescence

Hot electron luminescence experiments are performed[3] on ZnS ACTFEL devices in order to determine the extent to which the electron distribution is heated. The luminescence spectrum in broad and essentially featureless and is cut off at the ZnS band gap due to optical absorption. If the hot electron luminescence is presumed to arise from radiative transitions within the conduction band

of ZnS, this result indicates that a significant fraction of the electrons transported across the phosphor possess energies equal to or in excess of the ZnS band gap. One implication of this result[4] is that the extent of heating of the hot electron distribution is underestimated in our Monte Carlo simulations because the non-parabolic, three-valley model overestimates the density of states and, hence, underestimates the heating of the high energy tail of the distribution. However, more work is required before the hot electron luminescence can be unequivocally attributed to conduction band radiative recombination.

2. Defect State Hot Electron Sourcing and Trapping

(a) The Q-F_p Technique

A new approach for electrical characterization of ACTFEL devices, the internal charge versus phosphor field (Q-F_p) technique, is proposed.[5] Q-F_p analysis provides direct information about the internal device physics operation of an ACTFEL device. The steady-state field and internal conduction, polarization, leakage, and relaxation charges may be measured from a Q-F_p plot. Moreover, the phosphor and insulator capacitances may be deduced via Q-F_p analysis.

(b) Electrical Characterization of ZnS:Mn ACTFEL Devices

The internal device physics operation of evaporated and atomic layer epitaxy (ALE) ACTFEL devices are assessed[6,7] via charge-voltage (Q-V), capacitance-voltage (C-V),[8] and Q-F_p analysis as a function of systematic variations in the applied voltage waveform.

For both the evaporated and ALE devices it is found that the electrical response is most sensitive to the amplitude of the applied voltage pulse, least sensitive to the rise and fall times, with the pulse width sensitivity intermediate to that of the amplitude of the rise/fall time. The electrical response is found to be symmetric with respect to the polarity of the applied voltage pulse for an evaporated device but asymmetric for the ALE device; the asymmetry of the ALE device is attributed to an asymmetry of the interface state density and to the existence of space charge within the ALE-grown phosphor layer. Accurate electrical and optical equivalent circuit models for the evaporated ACTFEL device are devised.

(c) Space Charge in ALE ZnS:Mn ACTFEL Devices

Electro-optical measurements of ALE ZnS:Mn ACTFEL devices are employed[9] in order to assess the defect physics giving rise to the build up of space charge within such devices. These measurements lead to the identification of space charge in ALE ZnS:Mn devices as arising from the impact ionization of zinc vacancies within the ZnS.

(d) Interface State Assessment

The distribution of trapped electrons at interface states in ACTFEL devices is monitored using a new field-stimulated charge measurement technique.[10] This field-stimulated charge

measurement technique is then refined[11] through the development of a field-control circuit which holds the phosphor field constant between applied voltage pulses such that the ACTFEL interface state density can be directly measured. Preliminary measurements indicate that the interface state density rises sharply at about 0.9 eV below the conduction band minimum for ZnS ACTFEL devices, independent of how the ZnS is grown, how the insulators are deposited, or the type of insulator used.

(e) Impact Ionization in Evaporated ZnS:Mn ACTFEL Devices

Evidence is presented that the normal operation of evaporated ZnS:Mn ACTFEL devices involves electron-hole pair generation by band-to-band impact ionization. Four observations are offered to support this assertion. These observations involve: (i) empirical field-clamping trends, (ii) experimental and simulated trends in charge transfer characteristics, (iii) experimental attempts to assess the interface distribution using a field-control circuit, and (iv) Monte Carlo simulation trends. Furthermore, the absence of overshoot in measured C-V and Q-F_p curves indicates that a majority of the holes created by impact ionization are trapped at or near the phosphor/insulator interface. The multiplication factor (i.e., the total number of electrons transferred across the phosphor divided by the number of electrons injected from the phosphor/insulator cathode interface) is estimated, from device physics simulation of experimental trends, to be of order 4-8 for evaporated ZnS:Mn ACTFEL devices operating under normal conditions.

(f) Electrical Characterization of Blue ACTFEL Devices

The electrical characteristics of evaporated yellow ZnS:Mn and blue $CaGa_2S_4$:Ce TFEL devices are compared and contrasted using C-V and Q-F_p analysis. Evaporated ZnS:Mn TFEL devices exhibit nearly ideal electrical characteristics which are dominated by strong field-clamping due to the presence of a very large and abrupt density of interface states. In contrast, $CaGa_2S_4$:Ce TFEL devices do not exhibit field-clamping and possess a lower density of interface which are distributed over a broader range of energy. The $CaGa_2S_4$ interface states are deeper in energy than those of ZnS:Mn TFEL devices. The results of C-V and Q-F_p measurements suggest that the EL performance of the $CaGa_2S_4$:Ce blue phosphor could be improved if more carrier injection can be provided from the phosphor/insulator interface.

3. Hot Electron-Induced ACTFEL Aging

The aging characteristics of evaporated and ALE ZnS:Mn ACTFEL devices are studied[14,15] by monitoring the Q-V, C-V, and Q-F_p characteristics as a function of the aging time. The experimental trends lead to the following pictures for ZnS:Mn ACTFEL aging.

Aging of evaporated ZnS:Mn ACTFEL devices proceeds[14] by atomic rearrangement at the insulator/ZnS interface in such a manner that deep level, fixed charge states are created which trap electrons at deeper energies. Such trapping leads to a reduction of conduction and polarization charges and an increase in the turn-on voltage with aging time. It is likely that this interfacial atomic migration is stimulated by the thermalization energy dissipated by hot electrons after they impinge upon the conduction band discontinuity at the phosphor/insulator interface.

Aging trends of ALE ZnS:Mn ACTFEL devices are distinctly different than that observed for evaporated devices.[15] The electrical characteristics of ALE devices are asymmetric with respect to the applied voltage pulse polarity; the aging characteristics of such devices are asymmetric also. The aging characteristics of ALE devices are attributed to the asymmetrical presence of Cl near the bottom interface and its tendency to migrate into the ZnS during aging.

III. List of Publications

1. J.D. Davidson, J.F. Wager, and S. Kobayashi, "Aging Studies of ZnS:Mn Alternating-Current Thin-Film Electroluminescent Devices," *J. Appl. Phys. 71*, 4040 (1992).

2. J.F. Wager, A.A. Douglas, and D.C. Morton, "Electrical Characterization and Modelling of ACTFEL Devices," *Electroluminescence*, edited by V.P. Singh and J.C. McClure (Cinco Puntos Press, El Paso), p. 92, (1992).

3. A.A. Douglas and J.F. Wager, "Electrical Characterization and Modeling of ZnS:Mn ACTFEL Devices with Various Pulse Waveforms," 1992 Society for Information Display International Symposium, Boston, MA, May 1992.

4. K. Bhattacharyya, S.M. Goodnick, and J.F. Wager, "Monte Carlo Simulation of High Field Electron Transport in Alternating-Current Thin-Film Electroluminescent Devices," *Electroluminescence*, edited by V.P. Singh and J.C. McClure (Cinco Puntos Press, El Paso), p. 54, (1992).

5. S. Kobayashi, A. Abu-Dayah, and J.F. Wager, "Distribution of Trapped Electrons at Interface States in ACTFEL Devices," *Electroluminescence*, edited by V.P. Singh and J.C. McClure (Cinco Puntos Press, El Paso), p. 234, (1992).

6. A.A. Douglas and J.F. Wager, "ACTFEL Device Response to Systematically Varied Pulse Waveforms," *Electroluminescence*, edited by V.P. Singh and J.C. McClure (Cinco Puntos Press, El Paso), p. 387, (1992).

7. A.A. Douglas, J.F. Wager, D.C. Morton, J.B. Koh, and C.P. Hogh, "Evidence for Space Charge in Atomic Layer Epitaxy ZnS:Mn Alternating-Current Thin-Film Electroluminescent Devices," *J. Appl. Phys. 73*, 293 (1993).

8. A. Abu-Dayah, S. Kobayashi, and J.F. Wager, "Internal Charge-Phosphor Field Characteristics of Alternating-Current Thin-Film Electroluminescent Devices," *Appl. Phys. Lett. 62*, 744 (1993).

9. A. Abu-Dayah, J.F. Wager, and S. Kobayashi, "Electrical Characterization of ALE ZnS:Mn ACTFEL Devices," *SID 93 Digest*, 581 (1993).

10. A.A. Douglas, J.F. Wager, K. Bhattacharya, S.M. Goodnick, D.C. Morton, J.B. Koh, and C.P. Hogh, "Hot Electron Luminescence in ZnS ACTFEL Devices," *SID 93 Digest*, p. 851 (1993).

11. K. Bhattacharyya, S.M. Goodnick, and J.F. Wager, "Monte Carlo Simulation of Electron Transport in Alternating-Current Thin-Film Electroluminescent Devices," *J. Appl. Phys. 73*, 3390 (1993).

12. A.A. Douglas, J.F. Wager, D.C. Morton, J.B. Koh, and C.P. Hogh, "Hot Electron Luminescence in ZnS Alternating-Current Thin-Film Electroluminescent Devices," *Appl. Phys. Lett. 63*, 231 (1993).

13. A. Abu-Dayah, J.F. Wager, and S. Kobayashi, "Electrical Characterization of Atomic Layer Epitaxy ZnS:Mn Alternating-Current Thin-Film Electroluminescent Devices Subject to Various Waveforms," *J. Appl. Phys. 75*, 5575 (1993).

14. A. Abu-Dayah and J.F. Wager, "Aging Studies of Atomic Layer Epitaxy ZnS:Mn Alternating-Current Thin-Film Electroluminescent Devices," *J. Appl. Phys. 75*, 3593 (1994).

15. L.V. Pham, J.F. Wager, S.S. Sun, E. Dickey, R.T. Tuenge, and C.N. King, "Electrical Characterization of Blue Electroluminescent Devices," in Advanced Flat Panel Display Technologies, edited by P.S. Friedman, SPIE Proceedings 2174, 190 (1994).

16. S. Pennathur, K. Bhattacharya, J.F. Wager, and S.M. Goodnick, "Fullband Ensemble Monte Carlo Modeling of High-Field Transport in the ZnS Phosphor of AC Thin Film Electroluminescent Devices," International Workshop on Computational Electronics, Portland, OR, May 20, 1994.

17. S. Pennathur, K. Bhattacharya, S.M. Goodnick, and J.F. Wager, "A Full Band Monte Carlo High-Field Transport Simulation of the ZnS Phosphor in AC Thin-Film Electroluminescent Devices," (submitted to *J. Appl. Phys.*).

18. W.M. Ang, S. Pennathur, L. Pham, J.F. Wager, S.M. Goodnick, and A.A. Douglas, "Evidence for Band-to-Band Impact Ionization in Evaporated ZnS:Mn Alternating Current Thin-Film Electroluminescent Devices," (submitted to *J. Appl. Phys.*).

IV. List of Technical Presentations

1. Invited Talk: J.F. Wager, A.A. Douglas, and D.C. Morton, "Electrical Characterization and Modelling of ACTFEL Devices," *EL-92, Sixth International Workshop on Electroluminescence*, El Paso, TX, May 11-13, 1992 (Invited).

2. K. Bhattacharya, S.M. Goodnick, and J.F. Wager, "Monte Carlo Simulation of High Field Electron Transport in Alternating-Current Thin-Film Electroluminescent Devices," *EL-92, Sixth International Workshop on Electroluminescence*, El Paso, TX, May 11-13, 1992.

3. S. Kobayashi, A. Abu-Dayah, and J.F. Wager, "Distribution of Trapped Electrons at Interface States in ACTFEL Devices," *EL-92, Sixth International Workshop on Electroluminescence*, El Paso, TX, May 11-13, 1992.

4. A.A. Douglas and J.F. Wager, "ACTFEL Device Response to Systematically Varied Pulse Waveforms," *EL-92, Sixth International Workshop on Electroluminescence*, El Paso, TX, May 11-13, 1992.

5. A.A. Douglas and J.F. Wager, "Electrical Characterization and Modeling of ZnS:Mn ACTFEL Devices with Various Pulse Waveforms," 1992 Society for Information Display International Symposium, Boston, MA, May 1992.

6. A.A. Douglas, J.F. Wager, D.C. Morton, J.B. Koh, and C.P. Hogh, "Space Charge in ZnS:Mn Electroluminescent Devices," *Electrochemical Society Fall Meeting*, Toronto, Canada, October 11-16, 1992.

7. A.A. Douglas, J.F. Wager, D.C. Morton, J.B. Koh, and C.P. Hogh, "Hot Electron Luminescence in ZnS:Mn Electroluminescent Devices," *Electrochemical Society Fall Meeting*, Toronto, Canada, October 11-16, 1992.

8. A. Abu-Dayah, J.F. Wager, and S. Kobayashi, "Electrical Characterization of ALE ZnS:Mn Electroluminescent Devices," *1993 Society for Information Display International Symposium*, Seattle, WA, May 1993.

9. A.A. Douglas, J.F. Wager, K. Bhattacharyya, S.M. Goodnick, D.C. Morton, J.B. Koh, and C.P. Hogh, "Hot Electron Luminescence in ZnS ACTFEL Devices," *1993 Society for Information Display International Symposium*, Seattle, WA, May 1993.

10. Invited Talk: J.F. Wager, "Electroluminescence Research at OSU," OCATE Lectures in Advanced Technology, Beaverton, OR, January 21, 1994.

11. L.V. Pham, J.F. Wager, S.S. Sun, E. Dickey, R.T. Tuenge, and C.N. King, "Electrical Characterization of Blue Electroluminescent Devices," IS&T/SPIE Conference on Advanced Flat Panel Display Technologies, 7-8 February 1994, San Jose, CA.

12. Invited Talk: J.F. Wager, "Electroluminescence Research at OSU," OSU ECE Department Graduate Seminar, February 17, 1994.

13. Invited Talk: J.F. Wager, "Electroluminescence Research at OSU," OSU Department of Physics Colloquium, April 4, 1994.

14. Invited Talk: J.F. Wager, "Materials Issues for Thin-Film Electroluminescent Flat-Panel Displays," Oregon Materials Science Symposium, May 14, 1994.

15. S. Pennathur, K. Bhattacharya, J.F. Wager, and S.M. Goodnick, "Fullband Ensemble Monte Carlo Modeling of High-Field Transport in the ZnS Phosphor of AC Thin Film Electroluminescent Devices," International Workshop on Computational Electronics, May 20, 1994, Portland, OR.

Note that Presentations 1, 10, 12-14, and 16 were invited talks. Also note that Presentation 4 was awarded the Best Contributed Student Paper at the Society of International Display International Symposium.

V. List of Participating Scientific Personnel

1. James D. Davidson

   (i) M.S.; Thesis: "Capacitance-Voltage Analysis, SPICE Modeling, and Aging Studies of AC Thin-Film Electroluminescent Devices"
   (ii) Currently employed at: Intel, Aloha, OR

2. Allan A. Douglas

   (i) M.S.; Thesis: "Alternating-Current Thin-Film Electroluminescent Device Physics and Modeling"
   (ii) Currently employed at: Planar Systems, Beaverton, OR

3. Tin T. Nguyen

   (i) M.S.; Thesis: "Phosphor Development for Alternating-Current Thin-Film Electroluminescent Applications"
   (ii) Currently employed at: Intel, Aloha, OR

4. Ahmad Abu-Dayah

   (i) M.S.; Thesis: "Internal Charge-Phosphor Field Analysis, Electrical Characterization, and Aging Studies of AC Thin-Film Electroluminescent Devices"
   (ii) Currently employed at: Microsoft, Bellevue, WA

5. Keya Bhattacharya

   (i) PostDoc
   (ii) Currently employed at: Hewlett-Packard, Corvallis, OR

6. W.M. Ang

   (i) M.S.; Thesis: "ACTFEL Phosphor Deposition by RF Sputtering"
   (ii) Currently: Ph.D. Candidate, Oregon State University

7. Matthew R. Mueller

   (i) M.S.; Thesis: "Development of AlInN as an ACTFEL Phosphor"
   (ii) Currently employed at: Intel, Aloha, OR

8. Manoj Kumar

   (i) M.S. expected Fall 1994

9. Shankar S. Pennathur

   (i) Ph.D. expected Winter 1994

10. Long V. Pham

    (i) M.S. expected Spring 1994

11. Robert Thuemler

    (i) M.S. expected Winter 1995

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3. A.A. Douglas, J.F. Wager, D.C. Morton, J.B. Koh, and C.P. Hogh, *Appl. Phys. Lett. 63*, 231 (1993).

4. A.A. Douglas, J.F. Wager, K. Bhattacharya, S.M. Goodnick, D.C. Morton, J.B. Koh, and C.P. Hogh, *SID 93 Digest*, p. 851 (1993).

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7. A. Abu-Dayah, J.F. Wager, and S. Kobayashi, *J. Appl. Phys. 74*, 5575 (1993).

8. J.D. Davidson, J.F. Wager, I. Khormaei, C.N. King, and R. Williams, *IEEE Trans. Electron Devices ED-39*, 1122 (1992).

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10. S. Kobayashi, A. Abu-Dayah, and J.F. Wager, *Electroluminescence*, edited by V.P. Singh and J.C. McClure (Cinco Puntos Press, El Paso), p. 234, (1992).

11. A.A. Douglas, M.S. Thesis, Oregon State University (1993).

12. W.M. Ang, S. Pennathur, L. Pham, J.F. Wager, S.M. Goodnick, and A.A. Douglas, (submitted to *J. Appl. Phys.*).

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15. A. Abu-Dayah and J.F. Wager, *J. Appl. Phys. 75*, 3593 (1994).